Isoscalar Roper excitation in the $pp \rightarrow pp\pi^0$ reaction close to threshold

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ABSTRACT

A new mechanism for the $pp \rightarrow pp\pi^0$ reaction close to threshold is suggested coming from the isoscalar excitation of the Roper and its decay into $N(\pi\pi)_{s-wave}$, with one of the π^0 emitted and the other one reabsorbed on the second nucleon. The mechanism can lead to important interference with other mechanisms and, together with experiment, serves to exclude large ranges of the 2π N^* decay parameters allowed by the N^* partial decay widths.

1

1 Introduction

The large discrepancies between early calculations of the $pp \to pp\pi^0$ cross section close to threshold, based on the one body mechanism and the rescattering term [1, 2, 3, 4], and the experimental data [5, 6] have stimulated further work looking for a solution to the puzzle. Short range contributions associated to the isoscalar excitation of negative energy components on the nucleons were suggested as a possible explanation of the puzzle [7, 8] and similar ideas using exchange currents with heavy mesons have also been discussed [9].

It was soon realized [10] that because the rescattering process involves the isoscalar πN amplitude around threshold, and this amplitude is abnormally small on shell, off shell effects should be relevant since the πN amplitude appears there half off shell. Quantitative evaluations were done in [11] using two different off shell extrapolations in order to estimate uncertainties and it was shown that the use of the off shell extrapolations enhanced appreciably the cross section and could by itself explain the data. Further work along these lines was done in [12] improving on the small one body mechanism and using a different off shell extrapolation obtained from one version of the Bonn meson exchange model for the πN interaction [13].

The works of [11] and [12] share many things in common, with quantitative differences mostly due to the different off shell extrapolations used. In both cases a substantial increase of the cross section is found due to off shell effects (smaller in ref. [12]), together with a constructive interference between the one body and the rescattering terms.

The realization that QCD at low energies can be effectively taken into account by means of effective chiral Lagrangians [14] has led to the developments of Chiral Perturbation Theory (χPT) [15, 16, 17, 18], providing, in principle, and ideal tool to tackle the problem of the off shell extrapolation in the $pp \to pp\pi^0$ process. This has led to some work along these lines [9, 19, 20] with a main common feature, with respect to [11, 12], which is the negative interference between the one body and rescattering terms, opposite to the findings of [11, 12]. Another difference is the small cross sections obtained along these lines. This approach has been further revised in [21] where the authors note that several approximations done in the coordinate space treatment of former chiral approaches induced large uncertainties. The improved work of [21] in momentum space produces a much larger rescattering term and consequently larger cross sections. Yet, the interference between the one body and rescattering terms is negative as in former approaches.

Further clarifications on the chiral approach appear in the recent paper [22] which concludes that present χPT calculations are not yet at the level of providing quantitative results for the rescattering term. The large size of the momentum involved in the half off shell πN amplitude requires the evaluation of higher loops, and their corresponding counterterms. Actually, an accurate evaluation of this amplitude might as well require the use of non perturbative unitary techniques with coupled channels, as done in [23, 24, 25]. A very accurate description of K^-p scattering going to K^-p, $\bar{K}^0n$, $\Sigma^+\pi^-$, $\Sigma^-\pi^+$ and $\Lambda\pi^0$, together with the dynamical generation of the $\Lambda(1405)$ resonance below K^-p threshold was obtained in these works. One of the findings of [25] was the relevance of including the $\eta\Lambda$ and $\eta\Sigma^0$ channels in the approach, even if they are not open at low K^- energies, with some cross sections increased by a factor three due to the inclusion of these channels. This hints that the inclusion of coupled channels in the πN interaction might be relevant

even at pion threshold. Another result in [25] was the realization that $SU(3)$ symmetry, in the limit of equal masses, is broken unless all coupled channels from the octets of $1/2^+$ baryons and 0^- mesons are included in the coupled channel approach.

Further work along the lines of χPT is carried out in [26]. In this case pionic loops, including two pion exchange diagrams that might simulate σ exchange decaying into two π^0, one of which is emitted and the other one reabsorbed into the second nucleon, are included. An excellent agreement with experiment is claimed, even when the one body term is excluded. The same occurs in a OBE model by the same authors which explicitly accounts for the mechanism described above [27], which leads the authors to claim that this is the basic mechanism describing the process, irrespective of the formalism chosen. Other OBE models, not including that latter mechanism also claim to reproduce the data for $NN \rightarrow NN\pi$ in different isospin channels [28].

Undoubtedly much progress is being made, but the main conclusion might be that the process is more complicated than originally thought and that much work remains to be done.

The present work calls the attention on new mechanisms, not yet explored, and that could be relevant for the $pp \rightarrow pp\pi^0$ reaction, when considered in connection with the rescattering term, due to interference. The mechanism is related to Roper excitation and its decay into $N(\pi\pi)^{I=0}_{s=\text{wave}}$. This mechanism is present in most 2π production processes around threshold, $\pi N \rightarrow \pi\pi N$ [29, 30], $\gamma N \rightarrow \pi\pi N$ [31] and $NN \rightarrow NN\pi\pi$ [32]. In this latter process this mechanism is by far the dominant one around threshold in $pp \rightarrow pp\pi^+\pi^-$, $pp\pi^0\pi^0$, where the two pions can be in $I = 0$ and, within uncertainties, the agreement with data is acceptable. This gives us some confidence about the size of the mechanism evaluated here which corresponds to the dominant one for $pp \rightarrow pp\pi^0\pi^0$ in which one π^0 is emitted and the other one reabsorbed on the second nucleon.

2   Isoscalar Roper excitation in the $NN \rightarrow NN^*$ reaction

The clean experimental signal for $N^*(1440)$ excitation in (α, α') collisions on a proton target [33] provided evidence of a strong isoscalar excitation of the Roper in N N collisions. The experiment was analyzed in [34] by means of a model which included Δ excitation in the projectile (fig. 1a) together with Roper excitation on the target (fig. 1b), including the interference of both terms (for the part of $N^* \rightarrow N\pi$). For the isoscalar excitation of the Roper in diagram 1b an empirical amplitude was constructed assuming an effective "σ" exchange (although in a more microscopical picture it would be a combination of σ and ω exchange). This effective σ was assumed to have the same coupling to NN as in the Bonn model [35] while the coupling to NN^* was fitted to the data. The couplings used were

$$\frac{g^2_{\sigma NN}}{4\pi} = 5.69 \; ; \; \frac{g^2_{\sigma NN^*}}{4\pi} = 1.33 \tag{1}$$

and a monopole form factor with $\Lambda_\sigma = 1.7\,GeV$ together with $m_\sigma = 550\,MeV$, as in [35] were used. With this input, which contains $g_{\sigma NN^*}$ as the only parameter, a good reproduction of the data of [33] was obtained.

In the $NN \to NN\pi\pi$ reaction studied in [32] the same input for the isoscalar Roper excitation was used and the diagrams of fig. 2, together with the corresponding ones with N^* excitation on the first nucleon, plus 13 other mechanisms, including Δ excitation and chiral terms, were used. Contrary to the case of the (α, α') reaction where only the isoscalar exchange is allowed, here we can also exchange an $I = 1$ object, but is was shown in [32] that the strength of the isoscalar exchange was much larger than the corresponding one with $I = 1$, so here only the isoscalar excitation is considered. The results of [32] showed that in the $pp \to pp\pi^+\pi^-$ and $pp \to pp\pi^0\pi^0$ reactions the mechanisms of fig. 2 with $N^* \to N(\pi\pi)^{I=0}_{s-wave}$ dominated the cross sections close to threshold, where the other mechanisms either vanished or became very small.

With all this previous work described, there is then a clear mechanism which could be relevant for $pp \to pp\pi^0$ close to threshold and this is the one depicted in fig. 3, which corresponds to the same mechanism of fig. 2 for $2\pi^0$ production, where one of the pions is reabsorbed on the first nucleon, giving rise to the box diagrams of the figure. This is the mechanism which we evaluate in the next section.

3   Box diagram with isoscalar N^* excitation

For the evaluation of the box diagrams of fig. 3 we need the following Lagrangians:

$$\mathcal{L}_{\sigma pp}(x) = g_{\sigma NN} \ \bar{\Psi}_p(x)\Psi_p(x) \ \sigma(x)$$

$$\mathcal{L}_{\pi^0 pp}(x) = \frac{f_{\pi NN}}{m_\pi} \ \bar{\Psi}_p(x)\gamma^\mu\gamma_5\Psi_p(x) \ \partial_\mu\pi^0(x)$$

$$\mathcal{L}_{\sigma pN^*}(x) = g_{\sigma NN^*} \ \bar{\Psi}_{N^*}(x)\Psi_p(x) \ \sigma(x) + h.c.$$

$$\begin{aligned}
\mathcal{L}_{\pi^0\pi^0 pN^*}(x) &= g_{1\pi\pi NN^*} \ \frac{m_\pi^2}{f_\pi^2} \ \bar{\Psi}_{N^*}(x)\Psi_p(x) \ \pi^0(x)\pi^0(x) \\
&+ g_{2\pi\pi NN^*} \ \frac{1}{f_\pi^2} \ \bar{\Psi}_{N^*}(x)\Psi_p(x) \ \partial^0\pi^0(x) \ \partial^0\pi^0(x) + h.c.
\end{aligned} \tag{2}$$

The lagrangian $\mathcal{L}_{\pi^0\pi^0 pN^*}(x)$, with the second piece in its Lorentz covariant form, was first used in ref. [30] to evaluate the decay $N^*(1440) \to N(\pi\pi)_S$. In [30] the couplings $g_{1\pi\pi NN^*}$ and $g_{2\pi\pi NN^*}$ are called respectively $-c_1^*$ and $-c_2^*$. In this latter lagrangian we have set the energy of the Roper equal to its mass with respect to the formal one written in [30]. This is a good approximation in the present case. In that lagrangian f_π stands for the pion decay constant $f_\pi = 92.4 \ MeV$.

The couplings $g_{1\pi\pi NN^*}$ and $g_{2\pi\pi NN^*}$ are not fully known. The main constraint to their values comes from the study of the decay $N^*(1440) \to N(\pi\pi)_S$. In ref. [32] it is found that:

$$\Gamma_{N(\pi\pi)_S} = \alpha \ g_{1\pi\pi NN^*}^2 + \ \beta g_{2\pi\pi NN^*}^2 + \ \gamma \ g_{1\pi\pi NN^*} \ g_{2\pi\pi NN^*} \tag{3}$$

where $\alpha = 0.497 \ 10^{-3} \ GeV^3$, $\beta = 3.66 \ 10^{-3} \ GeV^3$ and $\gamma = 2.69 \ 10^{-3} \ GeV^3$. For $\Gamma_{N(\pi\pi)_S}$ they use a branching ratio of 7.5% and a total width of 350 MeV. The above ellipse is

not able by itself to fix both parameters and in fact, as seen in fig. 4, it spans over a large range of values. Further constraints were obtained in ref.[32] from an analysis of the $\pi^- p \to \pi^+ \pi^- n$ reaction data. Within the model used the experiment seemed to favour intermediate values in the ellipse. We also point out here that in ref. [30] the signs of both $g_{1\pi\pi NN^*}$ and $g_{2\pi\pi NN^*}$ are taken to be the same as the ones for the corresponding couplings in the $NN\pi\pi$ vertices. In this paper we will leave open the possibility for a different signs assignment.

The net contribution of the four diagrams to the invariant amplitude is given by

$$
\begin{aligned}
\mathcal{M} \;=\; & -2\, i\, g_{\sigma NN}\, g_{\sigma NN^*}\, \frac{f_{\pi NN}}{m_\pi} \int \frac{d^4 q}{(2\pi)^4}\, \left(g_{1\pi\pi NN^*}\, m_\pi^2 - g_{2\pi\pi NN^*}\, q^0 p_\pi^0 \right)\, \frac{1}{f_\pi^2} \\
& \times D_\pi(q)\, D_\sigma(p_3 - p_1 - q)\, (F_\pi(q))^2\, (F_\sigma(p_3 - p_1 - q))^2 \\
& \times \bar{u}_{s3}(\vec{p}_3)\, (\gamma^\mu \gamma_5 S_p(p_3 - q) + S_p(p_1 + q)\gamma^\mu \gamma_5)\, u_{s1}(\vec{p}_1) \\
& \times \{\bar{u}_{s4}(\vec{p}_4) S_{N^*}(p_4 + p_\pi + q) u_{s2}(\vec{p}_2) + \bar{u}_{s4}(\vec{p}_4) S_{N^*}(p_2 - p_\pi - q) u_{s2}(\vec{p}_2)\} \\
& + (\ exchange\ diagrams\ )
\end{aligned}
\tag{4}
$$

where we have included monopole form factors F_σ and F_π for each of the sigma and pion vertices. For the latter we use $\Lambda_\pi = 1.25\, GeV$. For the nucleon and Roper propagators we will take the positive energy part alone through the decomposition:

$$
S(p) = \frac{1}{2E(\vec{p})} \frac{E(\vec{p})\gamma^0 - \vec{p}\,\vec{\gamma} + m}{p^0 - E(\vec{p}) + i\epsilon} + \frac{1}{2E(\vec{p})} \frac{E(\vec{p})\gamma^0 + \vec{p}\,\vec{\gamma} + m}{p^0 + E(\vec{p}) + i\epsilon}
\tag{5}
$$

Due to energy denominators the positive energy part (first term in eq. (5)) should give, and in fact does, the dominant contribution to the amplitude.

The Roper contribution will be included on top of the rescattering term. As we will see the relevance of the Roper mechanism might show if not as a large absolute contribution yes with a large interference with the rescattering term. For the evaluation of the rescattering term we follow ref. [11]. We shall use the λ_1 parameter due to Hamilton [36], which for the half off-shell situation that we encounter here gives a larger value than the on shell $\lambda_1^{on-shell} = 0.0075$. In our case

$$
\lambda_1(q, p_\pi) = -\frac{1}{2}\, (1 + \epsilon)\, m_\pi\, \left(a_{sr} + a_\sigma\, \frac{m_\sigma^2}{m_\sigma^2 - (q + p_\pi)^2} \right)
\tag{6}
$$

with $\epsilon = m_\pi/M$ being M the nucleon mass, $a_\sigma = 0.220 m_\pi^{-1}$, $a_{sr} = -0.233 m_\pi^{-1}$ and $m_\sigma = 550\, MeV$. Note the q here has opposite sign to the one in ref. [11].

The complex structure of the amplitude in eq. (4) makes the evaluation of Final/Initial State Interactions Effects (FSI/ISI) a really hard task. We will not attempt here such a calculation and will content ourselves with the evaluation of the cross section without FSI/ISI. With these effects being very important near threshold, we can not make strong statements about the exact role played by the new mechanism but our hope is that we can get at least an indication of its relevance.

5

4   Results, discussion and conclusion.

In the following we show and comment the theoretical results obtained with different sets of values for $g_{1\pi\pi NN^*}$ and $g_{2\pi\pi NN^*}$.

In Table 1 we use $g_{1\pi\pi NN^*} = 7.27\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = 0$ which are the values favoured in the analysis of ref. [32]. As we see, the contribution of the Roper mechanism is by itself very small. The rescattering contribution alone is also small but, as shown in ref. [11], in this case FSI/ISI would bring theoretical predictions into a fairly good agreement with experimental data. When one takes the Roper and the rescattering terms together the interference gives a reduction of the rescattering prediction by roughly a factor of three. Thus, and although the Roper contribution alone is too small, the net effect is, through interference, to reduce significantly the contribution of the dominant rescattering term.

In Table 2 we use $g_{1\pi\pi NN^*} = 12.7\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = -1.98\ GeV^{-1}$. This set of values is quoted in ref. [32] as compatible with the experimental errors in the $\pi^- p \to \pi^+ \pi^- n$ reaction. Now the contribution of the Roper mechanism is comparable, though smaller, to the one of the rescattering term. The interference between the two is destructive and the net result is a very small cross section compared to the data.

In Table 3 the results shown correspond to $g_{1\pi\pi NN^*} = -12.7\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = 1.98\ GeV^{-1}$. This is as before but with opposite signs. Now the interference is constructive and the results at some energies are bigger than the data.

In Table 4 we have $g_{1\pi\pi NN^*} = 0$ and $g_{2\pi\pi NN^*} = 2.678\ GeV^{-1}$. The contribution of the Roper mechanism is very small but again the interference increases the results obtained with the rescattering term.

One can also choose a set of values for which the Roper mechanism alone overwhelms the data. This is done in Table 5 where we have used $g_{1\pi\pi NN^*} = -95.74\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = 34.61\ GeV^{-1}$ corresponding to one of the extremes of the ellipse. One would not expect FSI/ISI effects to bring the results closer to experiment in this case and such extreme situations have to be discarded. In fact these extreme cases are also excluded by the analysis of the $\pi^- p \to \pi^+ \pi^- n$ reaction.

We mention once again that we are not including FSI/ISI effects in the calculation. Thus, all the results presented here have to be taken with due caution as we know these effects are very important.

In spite of that crude approximation, we think that from the above results it emerges the fact that the Roper mechanism introduced here can be relevant for the understanding of the $pp \to pp\pi^0$ reaction. Even for the cases where the Roper contribution alone is too small, the interference with the dominant rescattering term is important. This situation is reminiscent of the role played by the Born or one-body term considered in calculations where FSI/ISI are included.

The second teaching of these calculations, is that, even at the qualitative level that we have analyzed the reaction, one can certainly exclude a wide range of values of $g_{1\pi\pi NN^*}$ and $g_{2\pi\pi NN^*}$ of the ellipse of fig. 4 allowed by the N^* decay into two isoscalar s-wave pions. It is clear that the values situated towards the extreme of the ellipse can easily be discarded and only values around the origin could be compatible with experiment, provided other mechanisms give sizeable contributions to the reaction. It is rewarding to see that such conclusions are in agreement with findings in ref. [32] coming from a more

detailed analysis for the $\pi N \to \pi \pi N$ reaction.

A more quantitative analysis of the mechanism discussed would be advisable although the FSI/ISI corrections would require lengthy calculations. At the present time, where so many different mechanisms are suggested, most of them claiming an explanation of the experiment, we feel that it suffices to show that this mechanism is there and that its interference with other mechanisms can completely change the results obtained ignoring it. With our knowledge about this reaction increasing with time and different mechanisms settling down on a firm basis, a future detailed study taking all these mechanisms into consideration would be an interesting task to tackle.

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Table 1: Cross sections for the $pp \to pp\pi^0$ reaction evaluated for different values of $\eta = p_{\pi\ max}/m_\pi$. Here $g_{1\pi\pi NN^*} = 7.27\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = 0$ (Point 1 in fig. 4). We show results for the Roper mechanism alone (σ_{Roper}), rescattering alone ($\sigma_{Rescat.}$), and the full calculation(σ_{Total}). For comparison we also show experimental data taken from ref. [5] All cross sections are in microbarns.

η	σ_{Roper}	$\sigma_{Rescat.}$	σ_{Total}	$\sigma_{Exp.}$
0.203	$1.7\ 10^{-2}$	0.10	$3.7\ 10^{-2}$	$0.70\ \pm\ 0.05$
0.306	$8.5\ 10^{-2}$	0.52	0.19	$1.91\ \pm\ 0.05$
0.407	0.26	1.6	0.56	$3.83\ \pm\ 0.11$
0.517	0.65	3.9	1.4	$6.18\ \pm\ 0.20$

Table 2: Same as Table 1 but with $g_{1\pi\pi NN^*} = 12.7\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = -1.98\ GeV^{-1}$ (Point 2 in fig. 4).

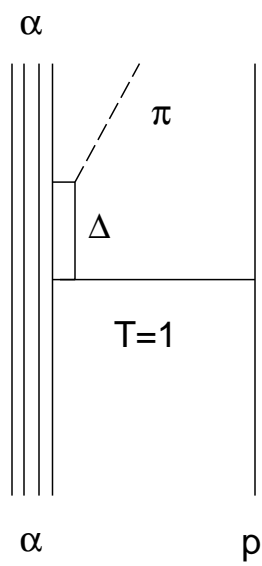| η	σ_{Roper}	$\sigma_{Rescat.}$	σ_{Total}	$\sigma_{Exp.}$
0.203	$6.6\ 10^{-2}$	0.10	$4.2\ 10^{-3}$	$0.70\ \pm\ 0.05$
0.306	0.33	0.52	$2.1\ 10^{-2}$	$1.91\ \pm\ 0.05$
0.407	1.0	1.6	$6.1\ 10^{-2}$	$3.83\ \pm\ 0.11$
0.517	2.6	3.9	0.15	$6.18\ \pm\ 0.20$

Table 3: Same as Table 1 but with $g_{1\pi\pi NN^*} = -12.7\ GeV^{-1}$ and $g_{2\pi\pi NN^*} = 1.98\ GeV^{-1}$ (Point 3 in fig. 4).

η	σ_{Roper}	$\sigma_{Rescat.}$	σ_{Total}	$\sigma_{Exp.}$
0.203	$6.6\ 10^{-2}$	0.10	0.33	$0.70\ \pm\ 0.05$
0.306	0.33	0.52	1.7	$1.91\ \pm\ 0.05$
0.407	1.0	1.6	5.1	$3.83\ \pm\ 0.11$
0.517	2.6	3.9	12.8	$6.18\ \pm\ 0.20$

Table 4: Same as Table 1 but with $g_{1\pi\pi NN^*} = 0$ and $g_{2\pi\pi NN^*} = 2.678 \; GeV^{-1}$ (Point 4 in fig. 4).
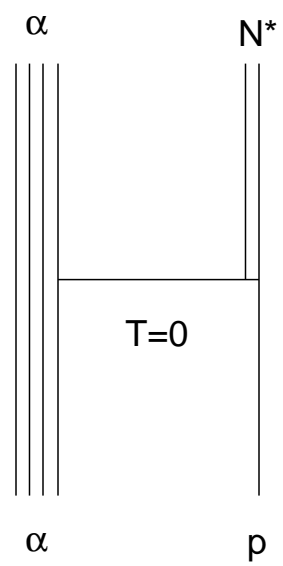
η	σ_{Roper}	$\sigma_{Rescat.}$	σ_{Total}	$\sigma_{Exp.}$
0.203	$1.8 \; 10^{-3}$	0.10	0.13	$0.70 \; \pm \; 0.05$
0.306	$9.1 \; 10^{-3}$	0.52	0.67	$1.91 \; \pm \; 0.05$
0.407	$2.8 \; 10^{-2}$	1.6	2.0	$3.83 \; \pm \; 0.11$
0.517	$7.3 \; 10^{-2}$	3.9	5.0	$6.18 \; \pm \; 0.20$

Table 5: Same as Table 1 but with $g_{1\pi\pi NN^*} = -95.74 \; GeV^{-1}$ and $g_{2\pi\pi NN^*} = 34.61 \; GeV^{-1}$ (Point 5 in fig. 4).

η	σ_{Roper}	$\sigma_{Rescat.}$	σ_{Total}	$\sigma_{Exp.}$
0.203	5.0	0.10	6.5	$0.70 \; \pm \; 0.05$
0.306	26	0.52	33	$1.91 \; \pm \; 0.05$
0.407	78	1.6	102	$3.83 \; \pm \; 0.11$
0.517	197	3.9	256	$6.18 \; \pm \; 0.20$

α   π

Δ

T=1

α   p

(a)

α   N*

T=0

α   p

(b)

Figure 1

Figure 2

Figure 3

Figure 4